Direct probes of flavor-changing neutral currents in e^+e^- collisions

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Based on A. Khodjamirian, T. Mannel, AAP, JHEP 1511 (2015) 142

1. Introduction: why rare decays?

★ Studies of the beauty FCNC transitions did not reveal large NP effects
- analyses now must rely on theoretical calculations to "sort out" NP

★ Can New Physics be "hiding" in the up-type quark transitions
- explicit models can be constructed where it can be done
- long-distance effects complicate interpretation
- must use exp and theo tricks to sort out

$$\mathcal{H}_{eff}^{SM} = -\frac{G_F}{\sqrt{2}} V_{cb}^* V_{ub} \sum_{i=7,9,10} \left(C_i \mathcal{O}_i + C_i' \mathcal{O}'_i \right)$$

$$\begin{aligned}
\mathcal{O}_7 &= \frac{e}{8\pi^2} m_c F_{\mu\nu} \bar{u} \sigma^{\mu\nu} (1+\gamma_5) c, \\
\mathcal{O}_9 &= \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \ell, \\
\mathcal{O}_{10} &= \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \gamma_5 \ell, \\
\mathcal{O}_7' &= \frac{e}{8\pi^2} m_c F_{\mu\nu} \bar{u} \sigma^{\mu\nu} (1-\gamma_5) c, \\
\mathcal{O}_9' &= \frac{e^2}{16\pi^2} \bar{u}_R \gamma_\mu c_R \bar{\ell} \gamma^\mu \ell, \\
\mathcal{O}_{10}' &= \frac{e^2}{16\pi^2} \bar{u}_R \gamma_\mu c_R \bar{\ell} \gamma^\mu \gamma_5 \ell,
\end{aligned}$$

Maybe correlations between different measurements can help sorting out NP in charm?

Any new ideas?

★ Two-body decays of D or B [a.k.a. B(D) → l^+l^-]

$$B^{(\mathrm{s.d.})}_{D^0\ell^+\ell^-} \simeq \frac{G_F^2 M_W^2 f_D m_\ell}{\pi^2} F\,,$$

- only one hadron to deal with: decay constant?
- but: probes limited number of operators, helicity suppression
  - e.g. not sensitive to vector-like New Physics (such as vector Z')
- soft photon effects preclude studies of electron decay modes:

$$\frac{\mathcal{B}(B_s \to \gamma\ell^+\ell^-)}{\mathcal{B}(B_s \to \ell^+\ell^-)} \propto \alpha \frac{m_B^2}{m_\ell^2}$$

★ Three-body decays of D or B [a.k.a. B(D) → M l^+l^-]

- probes several operators, many different observables
- but: two hadrons: four form-factors, hard to calculate non-perturbatively
- recent "issues" with lepton universality in B-decays

$$R_K = \frac{\mathrm{BR}(B \to K\mu^+\mu^-)}{\mathrm{BR}(B \to Ke^+e^-)} = 0.745^{+0.090}_{-0.074}\ (\mathrm{stat})\ \pm 0.036\ (\mathrm{syst})$$

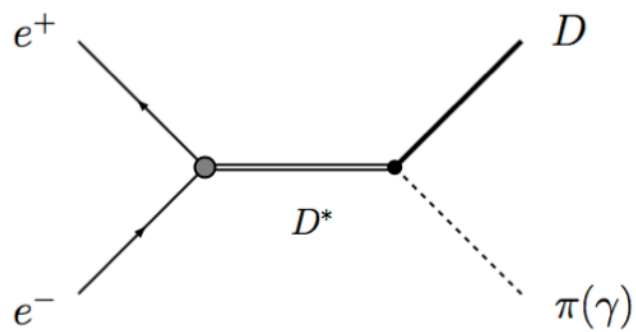
LHCb (2014)

Can one remove helicity suppression AND enlarge the set of probed operators by studying electroweak decays of excited states of D or B (like D* or B*)?

Studies of $D^*(B^*) \to e^+e^-$ in resonance production

★ Instead of searching for a decay of D*/B*, let's produce it!
- resonant enhancement possible if e+e- energy is tuned to $m_{D^*}(m_{B^*})$
- single heavy flavor + photon in the final state is a nice tag

Khodjamirian, Mannel, AAP
JHEP 11 (2015) 142

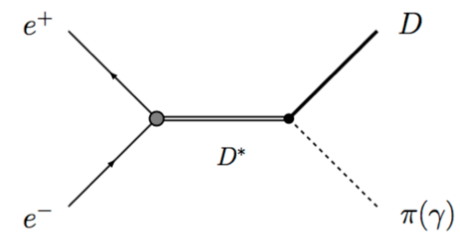


- contrary to a usual way of studying FCNC, production cross section is small

★ This way, the FCNC branching ratio for D*(2007) → e+e- is probed

$$\sigma(e^+e^- \to D\pi)_{\sqrt{s}\simeq m_{D^*}} \equiv \sigma_{D^*}(s) = \frac{12\pi}{m_{D^*}^2} \mathcal{B}_{D^*\to e^+e^-} \mathcal{B}_{D^*\to D\pi} \frac{m_{D^*}^2 \Gamma_0^2}{(s-m_{D^*}^2)^2 + m_{D^*}^2\Gamma_0^2},$$

Studies of $D^*(B^*) \to e^+e^-$ in resonance production



- Is it at all possible and feasible experimentally???

★ D* has a small width defined by strong and radiative decays

$$\Gamma_0 = \Gamma(D^{*0} \to D^0\pi^0) + \Gamma(D^{*0} \to D^0\gamma)$$
$$\simeq \frac{\Gamma_+ \mathcal{B}_{D^{*+}\to D^0\pi^+}}{2} \left(\frac{\lambda(m^2_{D^{*0}}, m^2_{D^0}, m^2_{\pi^0})}{\lambda(m^2_{D^{*+}}, m^2_{D^0}, m^2_{\pi^+})} \right)^{3/2} \left(1 + \frac{\mathcal{B}_{D^{*0}\to D^0\gamma}}{\mathcal{B}_{D^{*0}\to D^0\pi^0}} \right) \simeq 60 \text{ keV}$$

★ … with contributions from higher excitations being highly suppressed

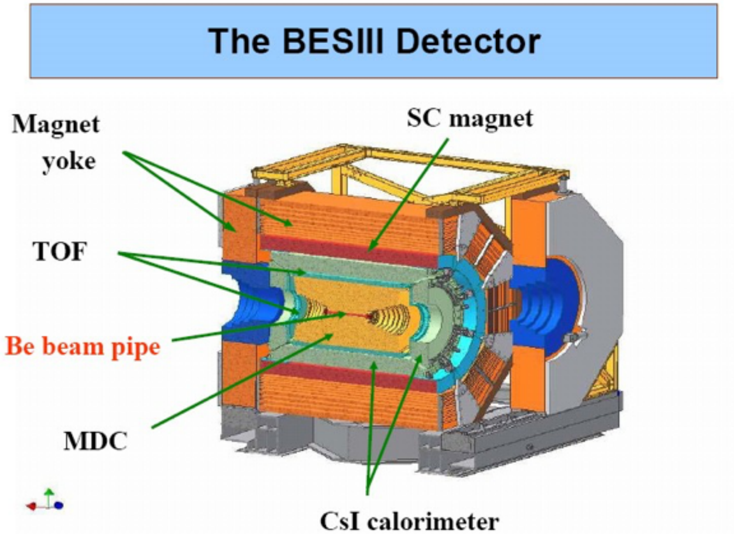
$$\left| \frac{f_{D^{0*\prime}}\, g_{D^{*\prime 0} D^0 \pi^0} m_{D^{*0\prime}}}{f_{D^{0*}}\, g_{D^{*0} D^0 \pi^0} m_{D^{*0}}} \right| \times \left| \frac{i\Gamma_0}{2\Delta - i\Gamma_{D^{*\prime}}} \right| \sim 5.0 \cdot 10^{-5}$$

★ … thus running for a "Snowmass year" (~10^7 s) with $L \approx 1.0 \times 10^{32}\ cm^{-2} s^{-1}$

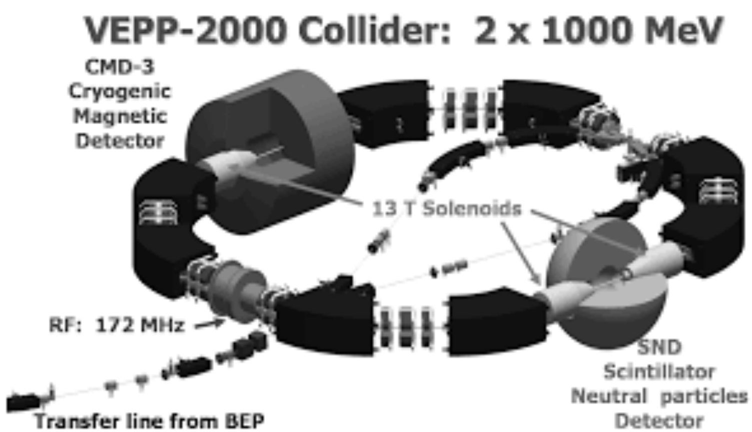
$$\mathcal{B}_{D^*\to e^+e^-} \geq \left(\frac{1}{\epsilon \int L dt} \right) \times \frac{m^2_{D^*}}{12\pi\ \mathcal{B}_{D^*\to D\pi}}.$$ probes $$\mathcal{B}_{D^*\to e^+e^-} > 4 \times 10^{-13}$$

Studies of $D^*(B^*) \to e^+e^-$ in resonance production

★ BEPCII machine with BESIII detector (China)
- optimized for Psi(3770)
- already made scans $\sqrt{s} = 2.0 - 4.2$ GeV.
- luminosity is about 5×10^{31} $cm^{-2}s^{-1}$



★ VEPP-2000 machine (Novosibirsk, Russia)
- optimized for E_{CM} < 2000 MeV
- possible upgrade to E_{CM} > 2000 MeV
- luminosity is about 1×10^{32} $cm^{-2}s^{-1}$



★ HIEPA: new tau-charm factory in Hefei (if approved)
-luminosity is about 5×10^{34} $cm^{-2}s^{-1}$

Calculation of D*(B*) → e⁺e⁻ in EFT

★ Most general effective Hamiltonian: $\langle e^+e^-|\mathcal{H}_{\rm eff}|D^*\rangle = G\sum_i c_i(\mu)\langle e^+e^-|\widetilde{Q}_i|D^*\rangle|_\mu$

$$
\begin{aligned}
\widetilde{Q}_1 &= (\bar{\ell}_L\gamma_\mu\ell_L)\;(\bar{u}_L\gamma^\mu c_L), \quad \widetilde{Q}_4 = (\bar{\ell}_R\ell_L)\;(\bar{u}_R c_L),\\
\widetilde{Q}_2 &= (\bar{\ell}_L\gamma_\mu\ell_L)\;(\bar{u}_R\gamma^\mu c_R), \quad \widetilde{Q}_5 = (\bar{\ell}_R\sigma_{\mu\nu}\ell_L)\;(\bar{u}_R\sigma^{\mu\nu} c_L),\\
\widetilde{Q}_3 &= (\bar{\ell}_L\ell_R)\;(\bar{u}_R c_L),
\end{aligned}
$$

plus L ↔ R

★ ... thus, the amplitude for D* → e⁺e⁻/μ⁺μ⁻ decay is

$$
A(D^*\to e^+e^-) = \bar{u}(p_-,s_-)\left[A\gamma_\mu + B\gamma_\mu\gamma_5 + \frac{C}{m_{D^*}}(p_+-p_-)_\mu + \frac{D}{m_{D^*}}(p_+-p_-)_\mu i\gamma_5\right] v(p_+,s_+)\;\epsilon^\mu(p),
$$

$$
\boxed{\mathcal{B}_{D^*\to e^+e^-} = \frac{m_{D^*}}{12\pi\Gamma_0}\left[\left(|A|^2+|B|^2\right)+\frac{1}{2}\left(|C|^2+|D|^2\right)\right]}
$$

$$
\begin{aligned}
A &= \frac{G}{4} f_{D^*} m_{D^*}\left(c_1+c_2+c_6+c_7\right),\\
B &= -\frac{G}{4} f_{D^*} m_{D^*}\left(c_1+c_2-c_6-c_7\right)
\end{aligned}
$$

Studies of $D^*(B^*) \to e^+e^-$ in the Standard Model

★ Standard Model, short distance:

- local O_9 and O_{10} operators
$$O_9 = \frac{e^2}{16\pi^2}\left(\widetilde{Q}_1 + \widetilde{Q}_7\right), \quad O_{10} = \frac{e^2}{16\pi^2}\left(\widetilde{Q}_7 - \widetilde{Q}_1\right)$$
- additional dipole contribution
$$H_{\rm eff}^{(7\gamma)} = \frac{4G_F}{\sqrt{2}} C_7^{\rm c,eff}\left(\frac{e}{16\pi^2} m_c\, \overline{u}_L \sigma^{\mu\nu} c_R F_{\mu\nu}\right)$$

★ Decay amplitude depends on additional non-perturbative parameter

$$\langle 0 | \overline{u} \sigma^{\mu\nu} c | D^*(p)\rangle = i f_{D^*}^T \left(\epsilon^\mu p^\nu - p^\mu \epsilon^\nu\right)$$

★ Short-distance result is well-defined

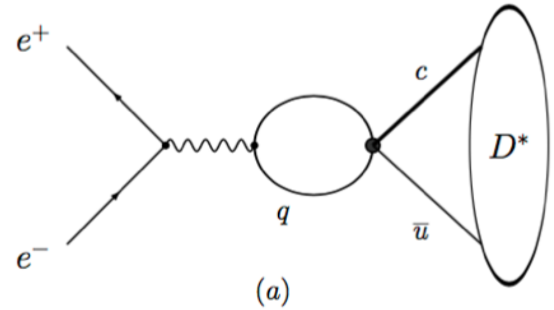
$$\mathcal{B}_{D^* \to e^+e^-} = \frac{\alpha^2 G_F^2}{96\pi^3 \Gamma_0} m_{D^*}^3 f_{D^*}^2 \left(\left| C_9^{\rm c,eff} + 2\frac{m_c}{m_{D^*}} \frac{f_{D^*}^T}{f_{D^*}} C_7^{\rm c,eff}\right|^2 + |C_{10}^{\rm c}|^2 \right)$$

★ … but the Br is small (the width is not though): $\mathcal{B}^{SD}_{D^* \to e^+e^-} = \dfrac{\Gamma(D^* \to e^+e^-)}{\Gamma_0} \approx 2.0 \times 10^{-19}$

No helicity suppression: no issues with testing lepton universality!

Studies of $D^*(B^*) \to e^+e^-$ in the Standard Model

- ★ Standard Model, long distance:
  - local O_1 and O_2 operators
  - additional penguin-like contribution



- ★ Decay amplitude:

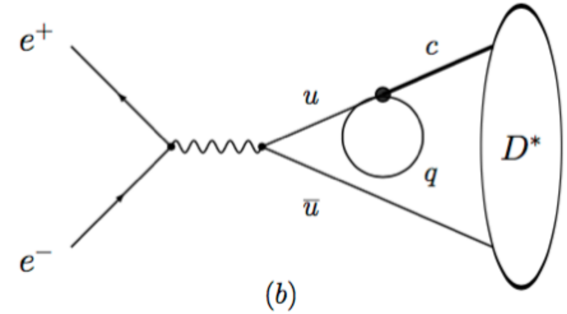
$$\langle e^+e^-|\mathcal{H}_w|D^*(p)\rangle = -e^2\bar{u}(p_-,s_-)\gamma^\mu v(p_+,s_+)\left(\frac{\Sigma_\mu(p^2)}{p^2}\right)\Bigg|_{p^2=m^2_{D^*}}$$

with $\Sigma_\mu(p^2) = i\int d^4x e^{ip\cdot x}\langle 0|T\left\{j^{em}_\mu(x)\mathcal{H}_w(0)\right\}|D^*(p)\rangle$

$$\Sigma^{(a)}_\mu(p^2) = \frac{G_F}{\sqrt{2}}\sum_{q=d,s}Q_q\left(C^{c(q)}_1+\frac{C^{c(q)}_2}{N_c}\right)\underbrace{\left\{i\int d^4x e^{ip\cdot x}\langle 0|T\left\{\bar{q}\gamma_\mu q(x)\ \bar{q}\gamma_\nu q(0)\right\}|0\rangle\right\}}_{\Pi^{(q)}_{\mu\nu}(p) = \left(-g_{\mu\nu}p^2+p_\mu p_\nu\right)\Pi^{(q)}(p^2)}$$
$$\times\ \langle 0|\bar{u}\gamma^\nu c|D^*(p)\rangle\,,$$

$$\Pi^{(q)}(p^2) = \frac{p^2}{12\pi^2Q_q^2}\int_0^\infty ds\frac{R^{(q)}(s)}{s(s-p^2-i\epsilon)}$$ with $$R(s)\equiv\frac{\sigma(e^+e^-\to hadrons)}{\sigma(e^+e^-\to\mu^+\mu^-)} = \sum_{q=u,d,s}R^{(q)}(s)$$

Studies of $D^*(B^*) \to e^+e^-$ in the Standard Model



★ Standard Model, long distance:
- local O_1 and O_2 operators
- additional penguin-like contribution

★ As a result:

$$\mathcal{B}^{LD,A}_{D^*\to e^+e^-} \simeq \begin{cases} 4.7\times 10^{-20} & \text{(NLO)} \\ 5.7\times 10^{-18} & \text{(LO)} \end{cases} \qquad \mathcal{B}^{(LD,b)}_{D^*\to e^+e^-} \geq (0.1 - 5.0)\times 10^{-19}$$

… and recall that the short distance $\mathcal{B}^{SD}_{D^*\to e^+e^-} \approx 2.0\times 10^{-19}$

★ Overall, the Standard Model contribution to $D^* \to e+e-$ is rather small, but
- it is four orders of magnitude higher than the Br($D \to e+e-$)!
- the long-distance contribution is moderate
- there is a large window to probe New Physics, as e.g. with BES-III

$$\mathcal{B}_{D^*\to e^+e^-} > 4\times 10^{-13}$$

Khodjamirian, Mannel, AAP (2015)

Any interesting New Physics scenarios?

$D^*(B^*) \to e^+e^-$: example of NP contribution

★ A plethora of NP models that realize charm (beauty) FCNC interactions can be probed
- consider a model with a Z′ coupling to a left-handed FCNC quark currents

$$\mathcal{L}_{Z'} = -g'_{Z'1}\bar{\ell}_L\gamma_\mu\ell_L Z'^\mu - g'_{Z'2}\bar{\ell}_R\gamma_\mu\ell_R Z'^\mu - g^{cu}_{Z'1}\bar{u}_L\gamma_\mu c_L Z'^\mu - \cancel{g^{cu}_{Z'2}}\bar{u}_R\gamma_\mu c_R Z'^\mu .$$

★ At low energies integrate out Z′:

$$\mathcal{L}^{Z'}_{\text{eff}} = -\frac{1}{M^2_{Z'}}\left[g'_{Z'1}g^{cu}_{Z'1}\widetilde{Q}_1 + g'_{Z'1}g^{cu}_{Z'2}\widetilde{Q}_2 + g'_{Z'2}g^{cu}_{Z'2}\widetilde{Q}_6 + g'_{Z'2}g^{cu}_{Z'1}\widetilde{Q}_7\right]$$

★ …which leads to a branching ratio (for $g'_{Z'1} = \frac{g}{\cos\theta_W}\left(-\frac{1}{2}+\sin^2\theta_W\right), \qquad g'_{Z'2} = \frac{g\sin^2\theta_W}{\cos\theta_W},$)

$$\mathcal{B}^{Z'}_{D^*\to e^+e^-} = \frac{\sqrt{2}G_F}{3\pi\Gamma_0} m^3_{D^*} f^2_{D^*} \frac{\left|g^{cu}_{Z'1}\right|^2}{M^2_{Z'}} \frac{M^2_Z}{M^2_{Z'}} \left(\frac{1}{4} - \sin^2\theta_W + 2\sin^4\theta_W\right)$$

★ … and current constraint of $\mathcal{B}^{Z'}_{D^*\to e^+e^-} < 2.5\times 10^{-11}$

Plenty of room in the parameter space to constrain

Anything different about $B^*_s \to e^+e^-$?

★ Experimentally:

- $m(B^*_s)$ = 5415.4 MeV, so need Belle II
- no phase space for $B^* \to B\pi$ decay
- considerably smaller total width

$$\Gamma^{tot}_{B_s^*} \simeq \Gamma(B_s^* \to B_s\gamma) = \frac{\alpha}{24}|g_{B_s^* B_s\gamma}|^2 \left(\frac{m^2_{B_s^*} - m^2_{B_s}}{m_{B_s^*}}\right)^3 \simeq 0.07 \text{ keV}$$

★ Standard Model contribution is rather large and unambiguous

- long-distance contribution is small

$$\mathcal{B}(B_s^* \to e^+e^-) = \frac{\alpha^2 G_F^2}{96\pi^3 \Gamma^{tot}_{B_s^*}} m^3_{B_s^*} f^2_{B_s^*} |V_{tb}V^*_{ts}|^2 \left(\left| C_9 + 2\frac{m_b}{m_{B_s^*}} \frac{f^T_{B_s^*}}{f_{B_s^*}} C_7^{\text{eff}} \right|^2 + |C_{10}|^2 \right)$$

$$\mathcal{B}_{B_s^* \to e^+e^-} = 0.98 \times 10^{-11}$$

★ Standard Model-type rate can be probed for similar luminosity 1×10^{32} $cm^{-2}s^{-1}$

$$\mathcal{B}(B_s^* \to e^+e^-) > 2.0 \times 10^{-12}$$

Khodjamirian, Mannel, AAP (2015)

Things to take home

- Indirect effects of New Physics at flavor factories help to distinguish among models possibly observed at the LHC in the future
  - a combination of bottom/charm sector studies
- Charm provides great opportunities for New Physics studies
  - contributions from New Physics are still possible
  - … but could be hidden by LD effects
  - need better estimate of LD effete: lattice?
- New reach: $D^*(B^*) \to e^+e^-$ can be studied with resonance production
  - plenty of parameter space for New Physics reach
  - probes New Physics models that $D(B) \to e^+e^-/\mu^+\mu^-$ are not sensitive to


EXTRA!

2d. Rare leptonic decays of charm

★ Standard Model contribution to $D \to \mu^+\mu^-$.

★ Short distance analysis

$$Q_{10} = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \gamma_5 \ell,$$

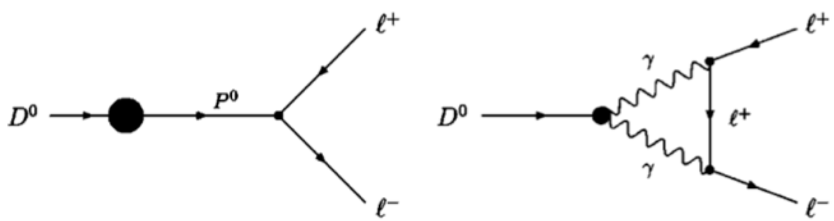
$$B^{(\mathrm{s.d.})}_{D^0 \ell^+ \ell^-} \simeq \frac{G_F^2 M_W^2 f_D m_\ell}{\pi^2} F\,,$$

$$F = \sum_{i=d,s,b} V_{ui} V^*_{ci} \left[\frac{x_i}{2} + \frac{\alpha_s}{4\pi} x_i \cdot \left(\ln^2 x_i + \frac{4+\pi^2}{3} \right) \right]$$

- only Q_{10} contribute, SD effects amount to Br ~ 10^{-18}
- single non-perturbative parameter (decay constant)

UKQCD, HPQCD; Jamin, Lange; Penin, Steinhauser; Khodjamirian

★ Long distance analysis



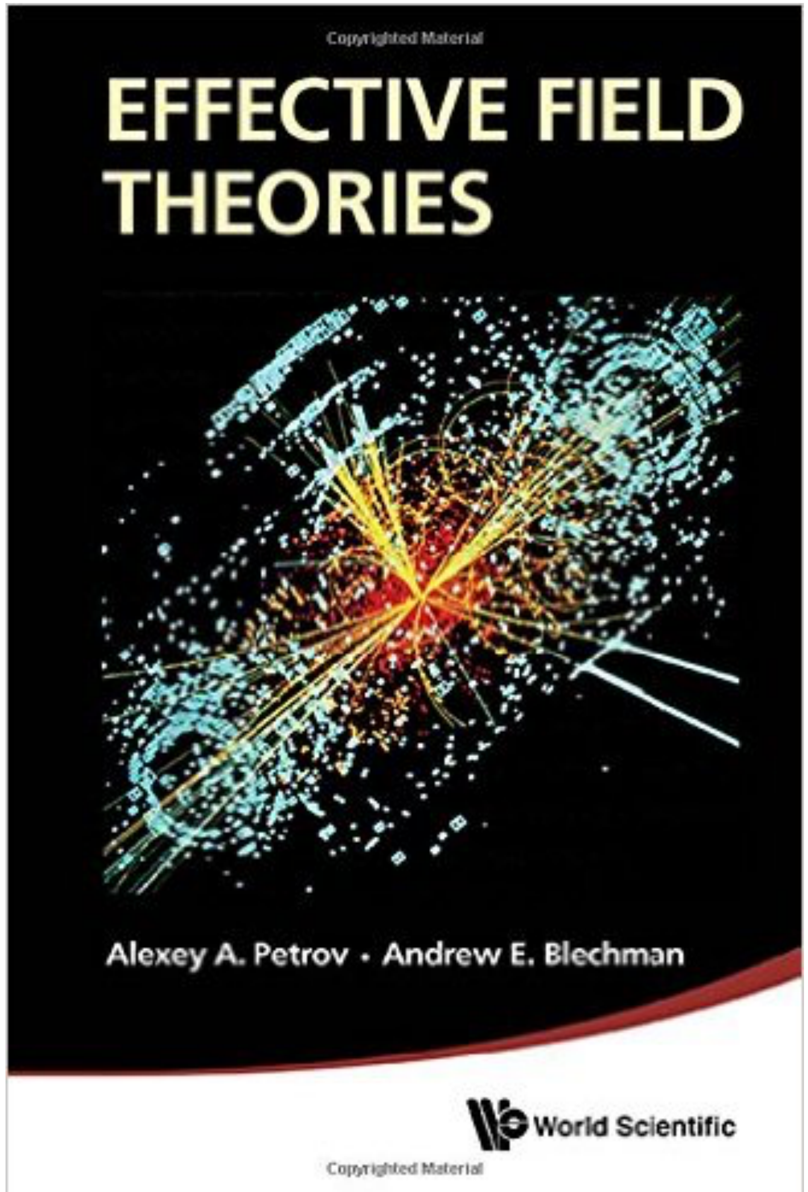
Burdman, Golowich, Hewett, Pakvasa; Fajfer, Prelovsek, Singer

Update soon: Healey, AAP

$$B^{(\mathrm{mix})}_{D^0 \ell^+ \ell^-} = \sum_{P_n} \langle P_n | \mathcal{H}^{(\mathrm{p.c.})}_{wk} | D^0 \rangle \frac{1}{M_D^2 - M_{P_n^2}} B_{P_n \ell^+ \ell^-}$$

$$\mathcal{Im}\, \mathcal{M}_{D^0 \to \ell^+ \ell^-} = \frac{1}{2!} \sum_{\lambda_1, \lambda_2} \int \frac{d^3 q_1}{2\omega_1 (2\pi)^3} \frac{d^3 q_2}{2\omega_2 (2\pi)^3} \times \mathcal{M}_{D \to \gamma\gamma} \mathcal{M}^*_{\gamma\gamma \to \ell^+ \ell^-} (2\pi)^4 \delta^{(4)}(p - q_1 - q_2)$$

- LD effects amount to Br ~ 10^{-13}
- could be used to study NP effects in correlation with D-mixing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